MEASUREMENT OF THE ENERGY SUPPLY FOR LOW VOLTAGE WIRE BRIDGE IGNITERS

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MEASUREMENT OF THE POWER REQUIREMENT FOR LOW VOLTAGE BRIDGE WIRE IGNITERS

M. Held

Abstract: Methods used to investigate the power required to ignite promers, electrical detonators, and electro-explosive devices in general are discussed. The measuring method must be chosen according to the kind of energy source. It makes a difference if the electro-explosive element must be ignited with energy stored in a capacitor, from a galvanic element with constant voltage, or from a magnetic generator with fixed current. Even the oldest kind of primer, the bridge wire, as is used in the model P 65, for instance, shows a number of interesting effects if it is started by different methods. They are discussed thoroughly. /25*

0.1. NOMENCLATURE

C	Capacitance	in Farads	[F]
E	Energy	in Joules	[J]
I	Current	in Amperes	[A]
N	Power	in Watts	[W]
R	Resistance	in Ohms	[Ω]
t	Time	in Seconds	[s]
τ	Time constant	in Seconds	[s]
U	Voltage	in Volts	[V]
t	time difference between ignition pulse and bridge wire breakage in the igniter with		
t_{D-I}	application of impressed current		
t_{D-U}	application of constant voltage		
t_{D-3U}	three times the voltage as compared to the limiting voltage for capacitor discharge		
t_L	light emission of the igniter at		
t_{L-I}	application of impressed current		
t_{L-Imp}	application of a current pulse		

*Numbers in the margin indicate pagination in the original foreign text.

t_{L-U}	application of constant voltage
$t_{L-Grenze}$	limiting voltage for capacitor discharge
t_{L-3U}	three times the voltage as compared to the limiting voltage for capacitor discharge
t_{Imp}	minimum pulse duration for igniter response to an applied current pulse.

1. INTRODUCTION /26

The objective is to test whether the output voltage of a magnetic pulse potential generator actuated manually is sufficient to ignite two P 65 igniters from the Gevelot company, connected in parallel [1].

The schematic diagram of the existing magnetic pulse potential generator is shown in Figure 1.

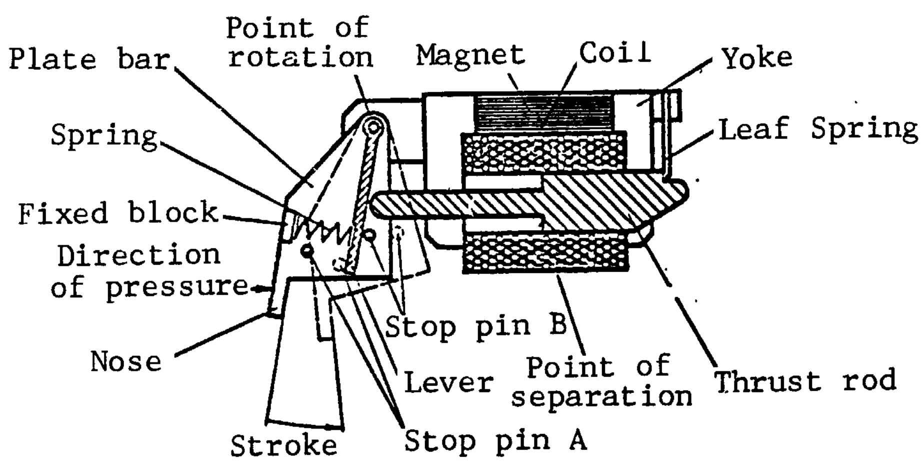

Figure 1. Schematic of the magnetic pulse potential generator

Pressure on the nose of the plate bar rotates it about its point of rotation. This further compresses the spring, which is prestressed between a fixed block on the plate bar and a lever. In the resting state, the lever lies against a stop pin B which is also fastened to the plate bar. The force of the spring, now more severely stressed, is still not enough to move the thrust rod against the holding force of the magnet and the leaf spring.

With sufficiently high pressure on the nose, and enough stroke, the spring becomes completely compressed and the force is transmitted directly from the plate bar to the stop pin A and the lever. Now, with increased force, the magnetic circuit is opened at the separation point, opposed by the magnetic force and the pressure of the leaf spring. After even slight opening of the magnetic circuit, the magnetic force decreases so strongly that the magnetic circuit is opened "rapidly" by the strongly pre-stressed spring, and a high-voltage induction pulse is produced.

The curve of the voltage produced by the magnetic pulse potential generator into 1 Ω resistance is shown in Figure 2. The energy output, from the oscillogram, is about 8 mJ.

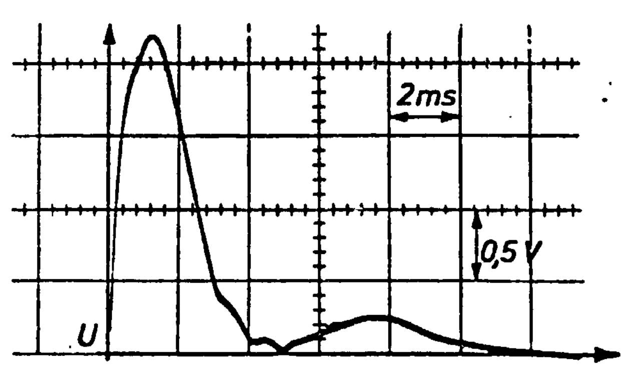

Figure 2. Voltage curve for the magnetic pulse potential generator working into 1 Ω load resistance.

Because two igniters connected in parallel should be caused to respond, for redundancy, we must confirm by measurements whether the energy is enough, particularly at the low output voltage of the generator, to ignite the two igniters throughout the desired temperature range with adequate reliability.

2. EXISTING DATA

A set of data can be found in the data sheets of the supplier company, Gevelot [1]. The data which are important for this study are reproduced in Figure 3. According to this, the igniter needs an energy of 1.5 mJ/Ω for response. As the bridge wire has a resistance of 2 ohms, then the energy requirement for <u>one</u> igniter is $2\,\Omega \cdot 1{,}5\ \mathrm{mJ}/\Omega = 3\ \mathrm{mJ}$.

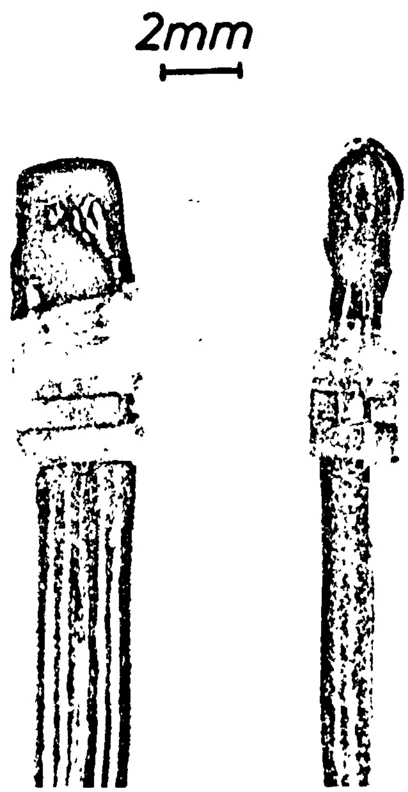

Figure 3. The P 65 igniter in profile and transverse views.

Ohmic resistance range	2 + 0.4 Ω
Response energy	1.5 + 0.5 mJ/Ω
Minimum response current	0.350 A
Normal firing current	1 A
Allowable measuring current	0.05 A
Response time at 1 A	2.5 + 1.5 ms
Allowable minimum temperature limit	-40°C

The quantity often cited for igniters, "mJ/Ω " is called "ignition impulse" in the literature [2, 3] and is introduced principally in industrial explosives technology. The statement of mJ/Ω can be useful for the design of igniters with incandescent bridges and for calculating the power requirement of igniters connected in series, along with the line resistances, although Ohm's law would serve as well here. When igniters are used separately, this statement has no advantage. When igniters are connected in parallel, this quantity even leads to incorrect /27
calculations. Furthermore, the statement of the "ignition impulse" in mJ/Ω has meaning only for igniters and electrical detonators having a resistance wire incandescent bridge. It has no significance at all for electrical detonators based on films [4] or gaps [5].

If we take the response time of 2.5 ms at a current of 1 A from the Gevelot data sheet [1] to calculate the energy per igniter, then from the energy formula

$$E = U \cdot I \cdot t \tag{1}$$

(U = voltage in volts, I = current in amperes, t = time in seconds, giving the energy in joules) we calculate an energy requirement of 5 mJ, as the voltage would be 2 V with a current of 1 A at a bridgewire resistance R of 2 Ω (Ohm's law: $U = I \cdot R$). Comparison of this calculated energy figure from the current and voltage measurements with time, 5 mJ, with the energy requirement given by the ignition impulse yields a difference of around 60%.

The Gevelot company also gives a curve of the response time t versus the applied current I (Figure 4, upper curve). From this, we can again calculate the energy E as a function of the current according to formula (1). This is plotted as the lower curve in Figure 4. According to this, the energy E increases considerably with increasing current. But this is

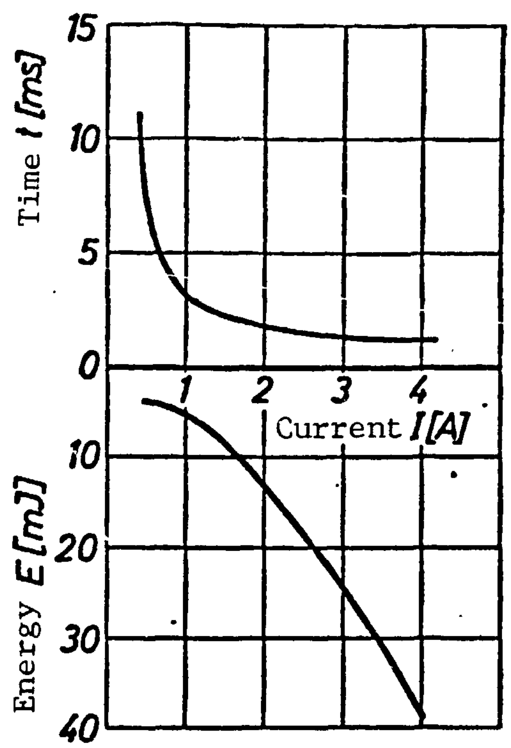

Figure 4. Response time t as a function of the current I, according to the data of the Gevelot company for the P 65 igniter, and the energy requirement E calculated from it as a function of the current.

not physically comprehensible, as the heating of the wire should occur properly with lower expenditure of energy because of thermal efficiency, at least in this current region. Here, apparently, the response time is determined by other processes, such as the reaction time of the ignition mixture.

The time from the beginning of current flow to response of the igniter or to detonation of electric detonators is called the "reaction time" in the pertinent literature [2]. But this expression is not very appropriate, because along with the reaction time proper there are other effects with a considerable time effect present in most different ignition mixtures in igniters or explosives in an electric detonator, such as the time to heat up the incandescent wire. For that reason, the more general expression "response time" is used here instead of the term "reaction time".

3. OUR OWN INVESTIGATIONS

We carried out investigations of our own in order to determine the exact energy requirement of the P 65 igniter. In order to obtain all data of interest for this igniter, they were submitted by the author to test methods applied for igniters and electrical detonators. In the following, we discuss all the measuring methods used and the results obtained with the P 65 igniter.

3.1 Response Threshold

For the manipulation of igniters and electrical detonators it is important to know the smallest current or voltage to which the igniters or electrical detonators will respond. For this reason, the first tests were performed essentially to determine /28
the response threshold of this element. The voltage of a power supply with low internal resistance was slowly increased from zero, and the voltage drop at the igniter and the current were measured continuously. The voltage applied or the current flowing at the response of the igniter gave the response threshold.

The response voltages U and minimum currents I obtained with this method for the P 65 igniter are plotted versus the bridge resistance R in Figure 5. The individual values scatter rather severely and show no relation to the bridge resistance. The minimum current of 0.35 A stated in the Gevelot data sheet agrees fairly with our measurements as the response threshold.

At a bridge resistance R of 2Ω a current I of 0.35 A was measured as the response threshold. Accordingly, we can calculate a voltage drop U of 0.7 V ($U = I \cdot R$). But we measured 0.74 V for this. This is due to the fact that the bridge wire was heated by the current so that its resistance increased, giving the greater voltage drop. (In this respect, see also the voltage increase at constant current in Figure 21.)

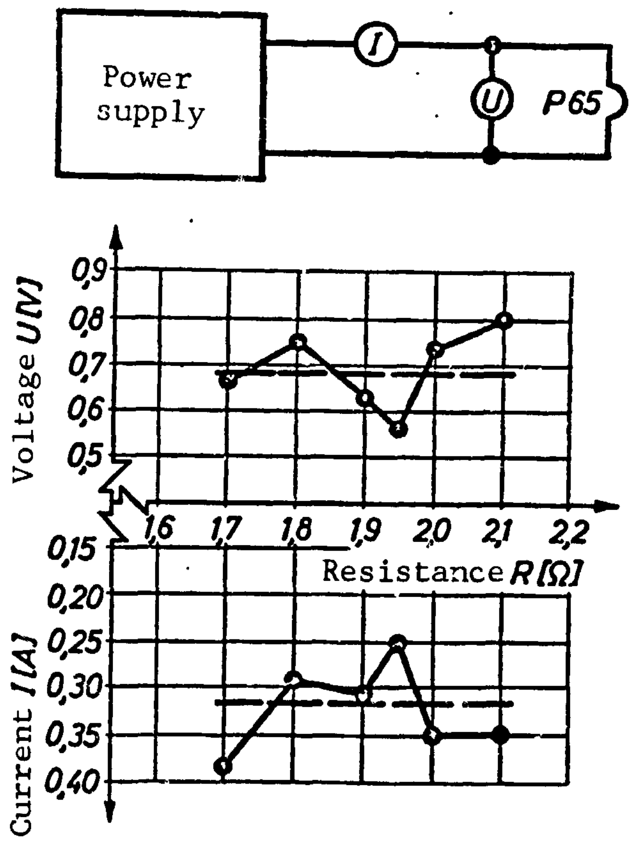

Figure 5. Response threshold of the P 65 igniter with respect to voltage U or current I, plotted versus the bridge resistance, R.

3.2 Determination of the Energy by Capacitor Discharge

In firing circuits, usually energy stored in a capacitor is switched to the igniter or the electrical detonator. For this reason, the energy requirement of "electrically actuated pyrotechnic articles" or "electro-explosive elements" – in English, "electro-explosive devices (EED)" – usually is also determined by capacitor discharge. The energy stored in a capacitor, E_c (in Joules) is calculated by the relation

$$E_c = \frac{1}{2}CU^2$$

where C is the capacitance in Farads and U the voltage of the charged capacitor in volts. This energy stored in the capacitor, E_c, is discharged through the igniter with a switch.

With a preselected capacitance C, one samples the limiting energy requirement of the igniter by stepwise increases of the voltage of the capacitor U. The resistance of the igniter is checked after each discharge.

By this multiple stressing of igniters or electrical detonators they can be "formed". That is, depending on the construction of the igniter or detonator, the response sensitivity can be displaced toward higher or lower values. As the purchaser of igniters, one can usually not work with large numbers of pieces. and can basically not perform the experiments with unstressed igniters in order to determine the statistical 50% response threshold, for instance. But in the money-saving multiple stressing, one must convince himself that the values are not displaced excessively by this multiple stressing. With the P 65 igniter, no effect on the resistance could be detected by this multiple stress.

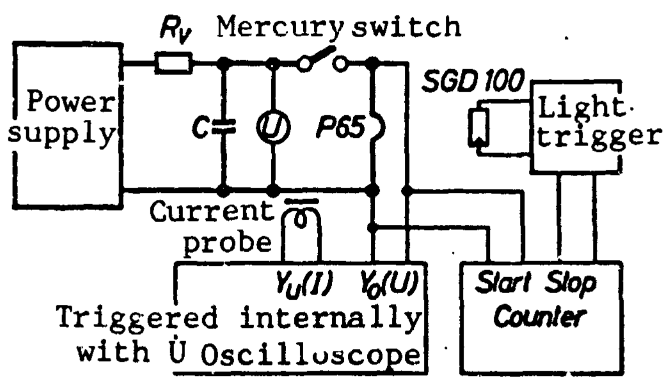

Figure 6. Circuit and measuring system for determining the energy requirement of igniters and electrical detonators by capacitor discharge.

Figure 6 shows the ignition circuit with the power supply, series resistance R_V, capacitor C and the mercury switch Hg. Use of mercury switches is necessary because mechanical switches are not free of bounce and the capacitor charge can be given off dropwise, so to speak, without the igniter necessarily responding. The voltage drop at the igniter, U, was measured with an oscilloscope, and the current was recorded at the same time by means of a clip-on probe. The ignition pulse simultaneously triggered the oscilloscope internally and started a counter. The counter was stopped again by means of the light flash from the responding igniter and a photoelement (SGD 100) with an amplifier and trigger unit (light trigger) so that the time difference between application of the voltage and appearance of a light emission at the igniter could also be measured.

The minimum voltage required to ignite the igniter, U, is plotted as a function of the various capacitances C in Figure 7, on a log-log scale. The measurements lie almost on the straight line with the slope ½, corresponding to the energy

$$E_c = 1/2\ CU^2 = 3\ [mJ] \tag{2a}$$

By plotting measurements of the minimum necessary energy E_C as a function of the capacitance C, the individual measurements become scattered in the diagram because of the quadratic dependence on U in the energy formula (Figure 8).

As Figures 7 and 8 show, the energy requirement of about 3 mJ given in the Gevelot data sheet is under-shot with capacitor discharges in the capacitance range from 1 to 100 µF. At 0.1 µF there is a mean energy requirement of about 3.5 mJ. This is a result of unsatisfactory matching of the electrical circuit to the low-resistance igniter, as the following oscillograms show (Figure 10). The increase in energy requirement at the capacitance of 1,000 µF is also due to non-ideal capacitors at these large values. At these low external resistances they show an internal resistance which is not negligible, so that terminal voltage,

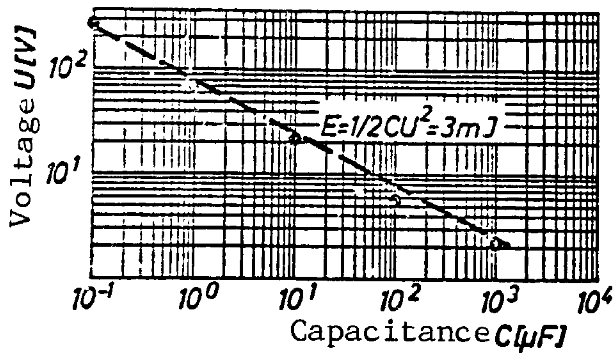

Figure 7. Minimum capacitor voltage U to ignite the P 65 igniter as a function of the capacitance C.

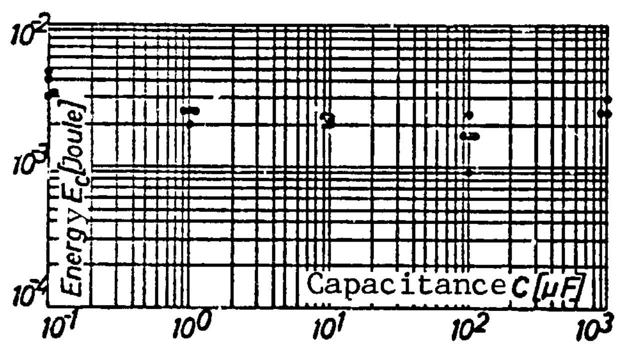

Figure 8. Minimum energy requirement E_c of the P 65 igniter as a function of the capacitance C, calculated from the energy stored in the capacitor, $E_c = \frac{1}{2} CU^2$.

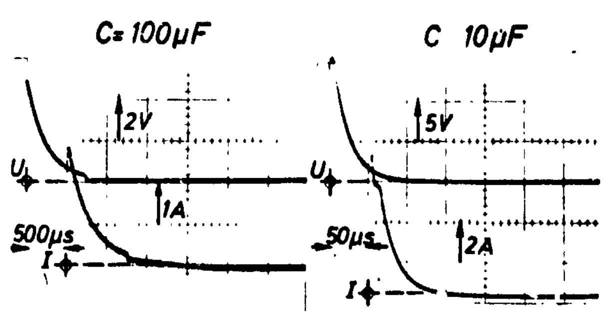

Figure 9. Voltage and current curves at the P 65 igniter on loading the igniter with the limiting energy by capacitor discharge with capacitances of 100 μF and 10 μF in the circuit of Figure 6.

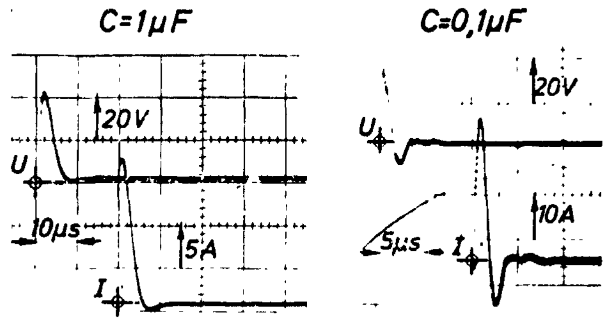

Figure 10. Voltage and current curves at the P 65 igniter on loading the igniter with the limiting energy by capacitor discharge with capacitances of 1 μF and 0.1 μF in the circuit of Figure 6.

on which the calculation of the energy requirement is based, does not correspond to the actual voltage drop at the igniter.

Furthermore, igniters require a certain energy in a certain time, that is, a certain power, in order to respond. A current of 0.05 A can be applied to the 65 igniter as long as one wishes without response. Here, the amount of energy provided can approach infinity. With a resistance of 2 Ω and a current of 0.05 A there is a voltage drop of 0.1 V, so that only 0.005 W can act on the igniters (power N = U · I; [W] = [V] · [A]). Because of thermal conductivity through the lead wires and through the igniter mixture, this low power is not enough to heat the bridge wire to the ignition temperature for the mixture. /29

As Figure 7 shows, the interesting voltage level of 2 V is not attained even with capacitances of 1,000 μF. Use of even larger capacitances is not practical, because, as already mentioned, these large capacitances no longer show negligible inductances and internal resistances, so that they are no longer suitable for a pulse discharge into low-resistance loads like these igniters. Therefore, other measuring circuits must be used to study the energy requirement of low-resistance igniters at low voltages.

From the course of the voltage drop at the igniter and from the curve of the current, recorded with a two-beam oscilloscope, the discharge behavior of the capacitors could be checked. The voltage drop can be taken from Figure 9 according to an exponential function for capacitances of 100 μF and 10 μF. The undershoot of the current curve is due to use of a clip-on current probe. The overshoot of the voltage curve at the capacitances of 1 μF and particularly 0.1 μF (Figure 10) is due to the insufficient matching of the electrical discharge circuit with the components used and the grouping with these low-resistance igniters.

The ignition time for the P 65 igniter was also determined with ten times the limiting energy, or 3.1 times the voltage as compared to the limiting voltage at the various capacitances. Some remarkable phenomena appeared here. At a capacitance of 1,000 μF the bridge wire is broken after about 0.5 ms, so that only a small part of the capacitor charge could be discharged through the bridge wire. The light from the igniter appeared only after about 6 ms. The oscillogram for the 1,000 μF discharge presented as an example (Figure 11) shows interruption of the bridge wire after 0.42 ms and 0.70 ms, respectively. Light emission occurred after a time delay t_{L-3U} of 5.9 and 6.7 ms, respectively.

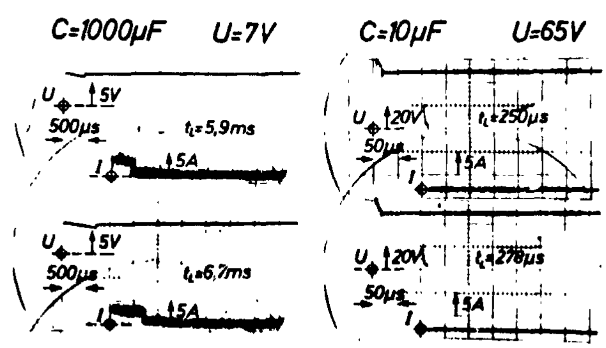

Figure 11. Voltage and current curves at the P 65 igniter on loading the igniter with ten times the limiting energy by discharge of capacitors with capacitances of 1,000 μF and 10 μF.

These oscillograms also show clearly that the capacitors with large capacitance do not show the desired low-resistance construction that is needed for studies of this type, because the voltage drops by some 15% when it is applied to the 2 Ω resistance of the igniter. After the bridge wire is broken, the voltage in the oscillogram again rises to the no-load voltage on the capacitor.

At 10 μF the capacitor likewise has discharged only to a small fraction. Here, the bridge wire is broken after 15 ms, on the average, while the light emission occurs after an average of 260 ms.

At the capacitance of 1,000 μF the voltage was 7 V; and at 10 μF, 65 V at first. But these voltages increase at 1 μF to 200 V and at 0.1 μF even to 750 V. At these high voltages, the small capacitances discharge completely, as the oscillograms of Figure 12 show. The bridge wire is broken in 5 μs at 1 μF and in 2 μs at 0.1 μF. At these high voltages, there is apparently

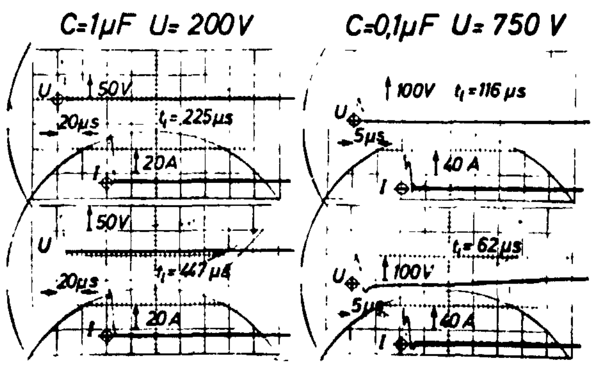

Figure 12. Voltage and current curves at the P 65 igniter on loading the igniter with ten times the limiting energy by discharge of capacitors with capacitances of 1 μF and 0.1 μF.

a "wire explosion", so that the entire stored electrical energy is given off as a spark discharge.

In spite of this wire explosion, the delay times for light emission average 240 μs for 1 μF and 95 μs at 0.1 μF. The time constants of the discharge circuit are shorter, or in the same order of magnitude, but the abrupt breakoff of the current and voltage curves according to Figure 12 suggests that the discharge of the capacitance was not by an exponential function, but along a steeper drop.

In Figure 13, the severely scattered delay times until light emission and bridge wire breakage, respectively, are plotted in a log-log diagram as functions of the capacitance.

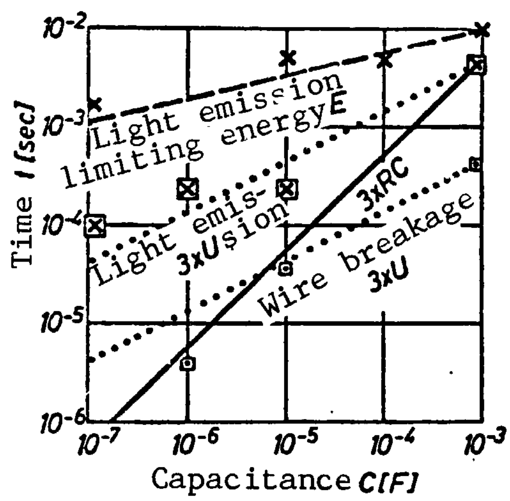

Figure 13. Time difference between application of the ignition pulse and appearance of light emission, or to breakage of the bridge wire, at the limiting energy E and at 10 times that energy (or at 3.1 times the limiting voltage U) as functions of the capacitance of the discharge capacitor for the P 65 igniter.

On application of the limiting energy to the igniter, the time difference to light emission, $t_{L\text{-}limit}$, decreases from 10 ms at 1,000 μF to 1 ms at 0.1 μF. The ruled line which is plotted corresponds to the equation (3):

$$t_{L-Grenze} = 56 \cdot 10^{-3}\, C^{1/4} \tag{3}$$

As the energy, $E = \frac{1}{2} CU^2$ in this region proves to be constant, the capacitance C can be replaced by the voltage U, substituting into Equation (3)

$$C = \frac{2E}{U^2} = \frac{2 \cdot 3 \cdot 10^{-3}}{U^2}. \tag{4}$$

so that

$$t_{L-Grenze} = \frac{16 \cdot 10^{-3}}{\sqrt{U}} \tag{5}$$

From the oscillograms, we cannot evaluate any times for the breakage of the bridge wire.

With capacitor discharges with ten times the limiting energy, there appear shorter times to light emission than on application of the limiting energy. This could be due to the bridge wire being heated faster and to higher temperatures, or to the ignition mixture reacting faster with the greater heat input. To a rough approximation, the averages can again be joined by a straight line (dotted line) in the log-log distribution, according to which the delay times t_{L-3U} now satisfy the equation

$$t_{L-3U} = 0{,}15 \sqrt{C} \tag{6}$$

The voltage U can again by substituted for the capacitance C:

$$C = \frac{2E}{U^2}, \text{ now with } E = 30 \cdot 10^{-3}, \text{ so that } C = \frac{60 \cdot 10^{-3}}{U^2} \tag{7}$$

In the range studied, the time delay t_{L-3U} between application of the ignition pulse and the light emission with ten times the limiting energy proves to be inversely proportional to the applied voltage:

$$t_{L-3U} = \frac{37 \cdot 10^{-3}}{U}. \tag{8}$$

The time difference until wire breakage, t_{D-3U} at ten times the limiting energy is smaller than that for light emission by about a power of ten. It satisfies the equation

$$t_{D-3U} = \frac{3{,}7 \cdot 10^{-3}}{U} \tag{9}$$

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Below a capacitance of $C = 10\ \mu F$ the capacitor discharges faster than calculated from Equation (9) for wire breakage. At the capacitance of $1\ \mu F$ we have a time constant

$$\tau = R \cdot C = 2\ [\Omega] \cdot 10^{-6}\ [\text{Farad}] = 2 \cdot 10^{-6} s \tag{10}$$

At three times the time constant, i. e., $3\tau = 6\ \mu s$, the capacitor has discharged to 5%. At later times, no wire breakage can be expected any more because of the low current. Therefore, this line is the upper time limit for wire breakage, and is shown in the diagram of Figure 13. The times for wire breakage at ten times the limiting energy are determined from Equation (9) and from Equation

$$t_{D-3U} = 3\tau = 3\ R \cdot C \tag{10a}$$

depending on which one gives the shorter time.

The faster breakage of the wire, and the slower appearance of light emission, by about a factor of ten, indicates that the reactive ignition mixture apparently requires both a certain starting time and a certain time to react.

If, on the other hand, the wire is heated very slowly with an appropriately small power, then it is primarily the heating time of the wire which determines the response time of the igniter. Thus, we must differentiate between two time-determining processes:

1. the heating of the wire
2. the reaction time of the ignition mixture until light emission occurs.

The latter, however, is a function of the heat flow – or, better, the heat shock – from the igniting wire. That is, the reaction time itself depends on the heating rate of the bridge wire. But this knowledge indicates that the required energy can not be calculated from the product of the applied current I, the voltage U, and the time delay t_L until emission of light according to Formula (1)

$$E = U \cdot I \cdot t_{light} \tag{1}$$

or, more exactly

$$E = \int_{t=0}^{t_{light}} U(t) \cdot I(t)\, dt, \tag{1a}$$

if U and I vary within the measuring period.

3.2 Application of Constant Voltage

In order to determine the energy requirement for response of the igniters at low voltages, voltages from a voltage source with low internal resistance were applied to the P 65 igniters. The curves for current and voltage and the time until the igniter emitted light were measured as described previously.

The voltage increases somewhat after the igniting wire breaks, as the oscillograms of Figure 15 show, as the constant voltage source which was used did not have sufficiently low resistance. But the breakage of the igniting wire could be measured well from this. From the oscillographic recordings of the voltage curves, furthermore, we can measure the exact voltage drop at the igniter for the power calculation.

In the oscillogram of Figure 15, presented as an example, the time difference between application of the igniting voltage and breakage of the igniter wire was 8.5 ms (upper trace). Stopping of the counter gave an 8.3 ms time difference between the ignition pulse and light emission. In this case the igniting voltage was 0.82 V. In the lower part of Figure 15, the time

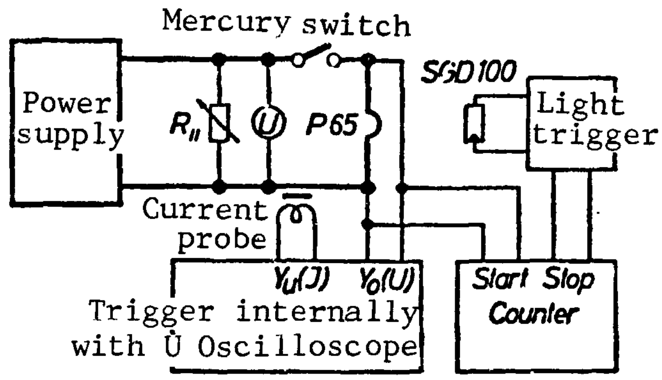

Figure 14. Circuit and measuring system for application of constant voltage to igniters or electrical detonators.

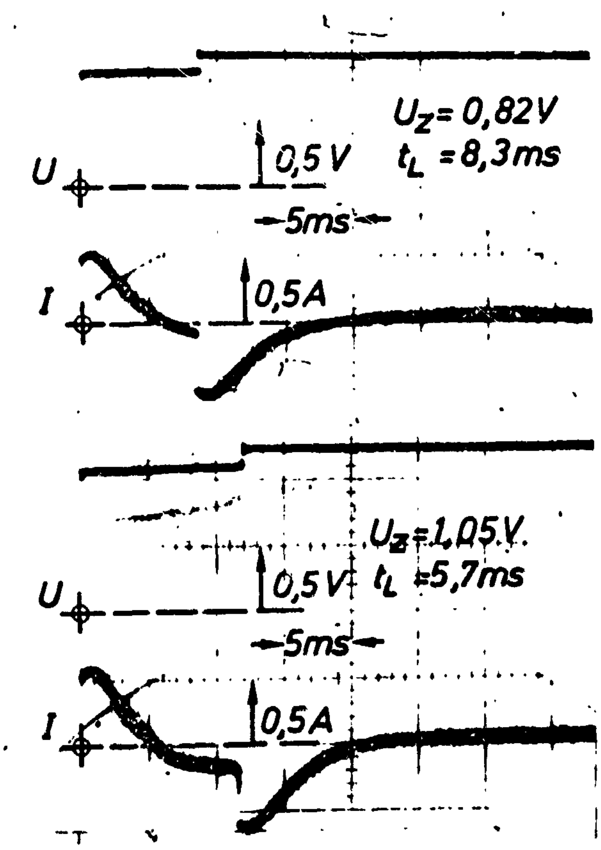

Figure 15. Current and voltage curves at the P 65 igniter on application of a constant low voltage, after switching.

difference until wire breakage was 11.8 ms, in spite of the higher ignition voltage, 1.05 V. The time difference until light emission was measured at only 5.7 ms.

Now, apparently at low voltages, the opposite case from capacitor discharge can appear. Namely, light emission appears <u>earlier</u> than breakage of the igniting wire, which is heated only slowly. This indicates that the ignition mixture will react after some certain heating of the wire, without the igniting wire necessarily having to be broken.

On capacitor discharge with energy ten times the limiting energy, the igniting wire breaks before the reactive mixture reacts, as already explained. /32

This means that the measurement of the time to breakage of the igniting wire, t_D, is not representative of the necessary energy ($U \cdot I \cdot t_D$) with a low potential difference across the igniting wire, because this does not determine the time which is already sufficient to cause the ignition mixture to react. As mentioned previously, we can likewise not use the time delay until light emission, t_L, because the time for the reaction to go through the igniting charge is unknown and is also a function of the heat shock.

Aside from measurements at small potential differences (low voltages) beyond 0.75 V, the measurement of the time delays between application of the voltage and light emission or wire breakage were continued up to constant voltages of 200 V. As different lots of igniters were used for this, the measurements scatter severely. If we plot the time delays until light emission or wire breakage on log-log paper as functions of the voltage, we find the following:

a) The values for "light emission" lie fairly well along a straight line, satisfying the equation

$$t_{L-U} = 6{,}5 \cdot 10^{-3} U^{-1} \qquad (11)$$

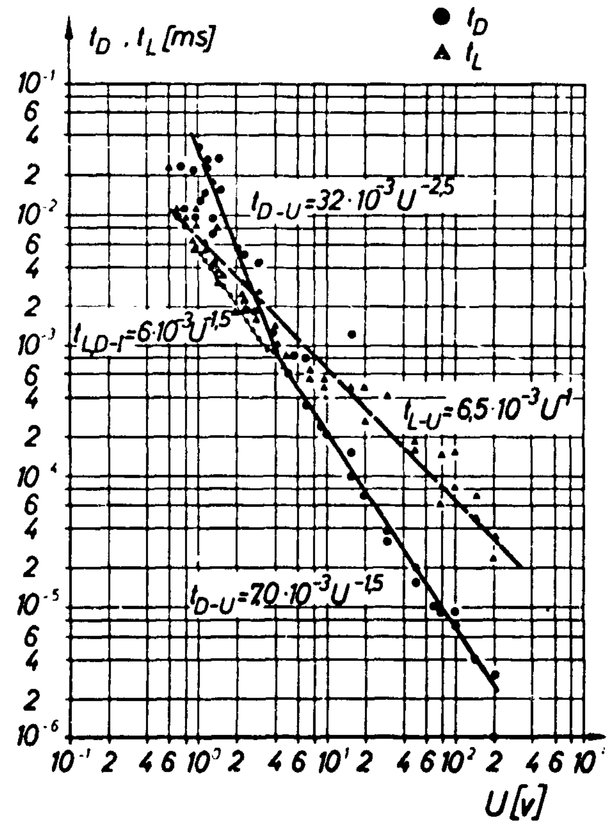

Figure 16. Time difference between the ignition pulse and breakage of the bridge wire, t_{D-U} or light emission t_{L-U} as a function of the applied voltage U for the P 65 igniter.

Except for the value of the constants ($6.5 \cdot 10^{-3}$ instead of $37 \cdot 10^{-3}$), this equation (11) agrees in the power of the voltage with Equation (8). The constant has a lower value. That is, the times are shorter with constant voltage than with capacitor discharge. This is understandable, because the voltage decays very rapidly with capacitor discharge, so that the energy flux through the igniter becomes smaller.

b) On the other hand, no <u>single</u> equation can reproduce the "wire breakage" The measurements are best reproduced by two straight lines. In the range from 0.75 V to about 4 V the equation of the line is

$$t_{D-U1} = 32 \cdot 10^{-1} \cdot U^{-2,5} \qquad (12)$$

and from 4 V to 200 V, the equation is

$$t_{D-U2} = 7{,}0 \cdot 10^{-3} \cdot U^{-1,5} \qquad (13)$$

At higher voltages one would expect constant energy for wire breakage. It is surprising that the energy requirement is not constant at higher voltages, but instead more and more energy must be applied before the bridge wire breaks. If the energy were constant, then U^{-2} (instead of $U^{-1.5}$) would appear in the equation, because according to (1)

$$E = U \cdot I \cdot t_{D-U} = \frac{U^2}{R} \, t_{D-U} \qquad (1b)$$

For E = constant, we would obtain

$$t_{D-U} = \frac{R \cdot \text{const.}}{U^2} = B \cdot U^{-2} \qquad (1c)$$

with B as a new constant. This can perhaps be explained by the chemical mixture around the bridge wire "assisting" the electrical energy to heat the wire.

On the other hand, the fact that a power larger than 2, namely 2.5, appears at low voltages is understandable because energy is lost by thermal conduction, as already mentioned.

The region studied can be divided into 3 ranges:

1. A range up to about 3 V, in which the light flash appears before the bridge wire breakage.

   Here, the bridge wire is heated very slowly, so that the ignition mixture reacts throughout before the energy to break the bridge wire is added from outside.

2. A range from about 3 to 6 V, where bridge wire breakage and the light flash occur almost simultaneously.

This range could be defined by the effect that the bridge wire, heated almost to the point of breakage, is broken by the additional thermal energy of the ignition mixture reaction.

3. A range beyond about 6 V, in which the bridge wire is broken before the light flash appears. /33

In this region, so much energy is added to the bridge wire that it is broken before the ignition mixture has had time to react through. Here the reaction time of the ignition mixture is not constant, but apparently depends on the heating rate and so on the heat introduced. Otherwise we would be unable to understand why the times to light emission also become steadily shorter as the voltage becomes higher and the times to wire breakage become shorter.

3.4 Application of Constant Current

The magnetic pulse generator is not a voltage source, but a current source. Therefore, the energy requirement for the igniter was also studied with constant current. In order to detect possible differences in the power matching (see later), different series resistances, 10, 30, and 100 ohms, were used.

As explained under section 3.1, the resistance change of the bridge wire on heating is less than 0.1 ohm. This means that with the 10 ohm series resistance the current is constant to within 1% in spite of the change in the igniter bridge resistance. The voltage and current curves and the time differences between the ignition pulse and light emission were determined as for the previous measurements (Figure 17).

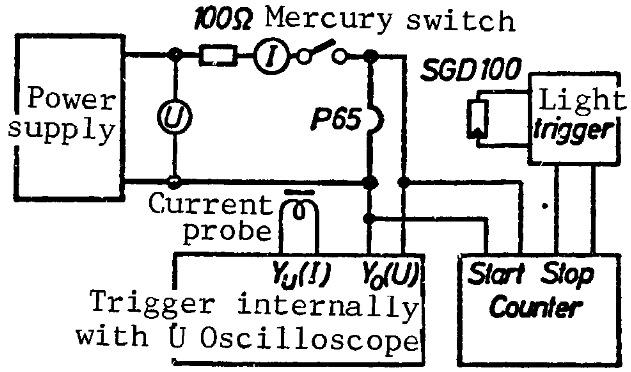

Figure 17. Circuit and measuring system for application of constant current to low-resistance igniters or electrical detonators. The 100 ohm series resistance can be varied as needed.

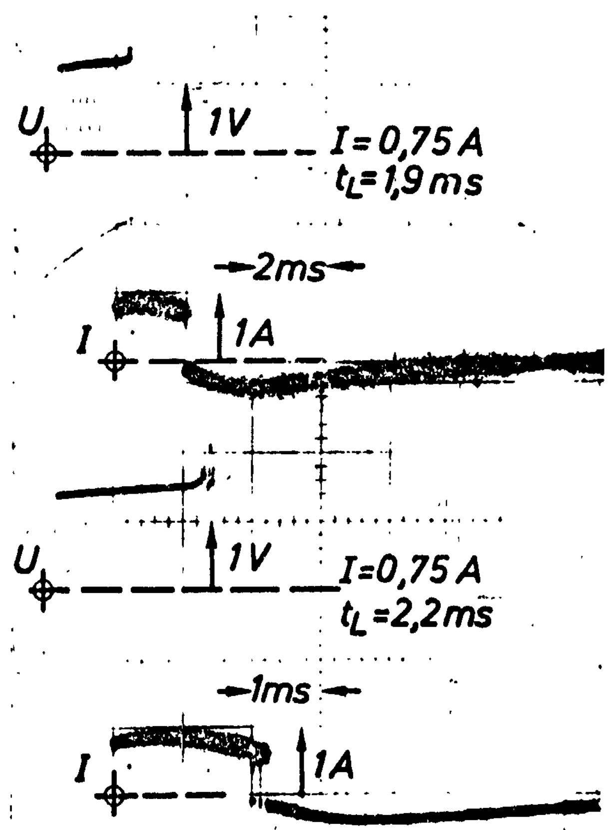

Figure 18. Example of the current and voltage curves at a P 65 igniter with application of constant current according to the circuit of Figure 17, with a 100 ohm series resistance.

In this circuit, the bridge wire sometimes breaks the circuit with flutter or bounce phenomena as with a mechanical switch. This appears particularly clearly, for example, in the lower oscillogram of Figure 18. The voltage increases, when the wire breaks, to the no-load voltage of the power supply, so that the oscilloscope trace moves up off the picture. The oscillation in the current curve is again due to the clip-on current probe, which does not carry the DC portion.

The time differences from the igniting pulse to breakage of the igniter bridge wire or to light emission with constant current are about equally long, to a first approximation. No dependence on the choice of series resistance could be found. All the measurements, which are plotted in Figure 19 on log-log paper as a function of the constant current with the series resistance as parameter, can be shown by a line described by the following equation:

$$t_{D-I} = t_{L-I} = 2{,}2 \cdot 10^{-3}\, I^{-1/5} \tag{14}$$

If I is replaced by U

$$(I = U/R = U/2;\ I^{-1/5} = (U/2)^{-1/5} = 2{,}8 \cdot U^{-1/5}),$$

then we obtain

$$t_{D-I} = t_{L-I} = 6{,}2 \cdot 10^{-3}\, U^{-1/5}. \tag{15}$$

This line was plotted as the dotted line in Figure 16 in the range of 0.5 A, corresponding to 1 V of voltage drop, and 2 A, corresponding to a drop of 4 V. It is interesting to note that it is a continuation of Equation (13) in Figure 16, except for a slight difference in the constants (6.2 instead of 7.0, which is within the measuring accuracy).

This line is properly in the first voltage range (according to the definition in Section 3.3), where the light emission occurs faster than wire breakage. This tendency is present, although weaker, at currents of 0.5 and 0.75 A, corresponding to 1 and 1.5 V. At 1.5 and 2 amperes, corresponding to 3 and 4 V, we have, within the limits of error, practically simultaneous appearance of light emission and wire breakage.

One explanation of this phenomenon would be that higher powers can be converted on breakage of the bridge wire in the P 65 igniter with constant current than with constant voltage. This would then lead to faster reaction in the ignition mixture. As can be seen from Figure 15, the ignition mixture reacts through within 100 μs at high voltage and, therefore, high power. Here, with a total response time of some milliseconds, this is within the accuracy of measurements.

An example calculation may clarify this:

Let the power supply be adjusted to 102 V, so that a current of 1 A flows through the series resistance of 100 ohms and the 2 ohm igniter.

$$I = \frac{U}{R}, I = \frac{102\ [V]}{100+2\ [\Omega]} = 1\ [A] \qquad (16)$$

At the 2 ohm igniter, there is a 2 V voltage drop at 1 A current

$$U = I \cdot R = 1\ [A] \cdot 2\ [\Omega] = 2\ [V] \qquad (17)$$

From this we can calculate the power in watts applied to the igniter

$$N = U \cdot I = [V] \cdot 2\ [A] = 2\ [W] \qquad (18)$$

Now assume that during breakage, the bridge wire also experiences a resistance of 100 ohms. At this moment, the circuit, including the series resistance, has a total resistance of 200 ohms.

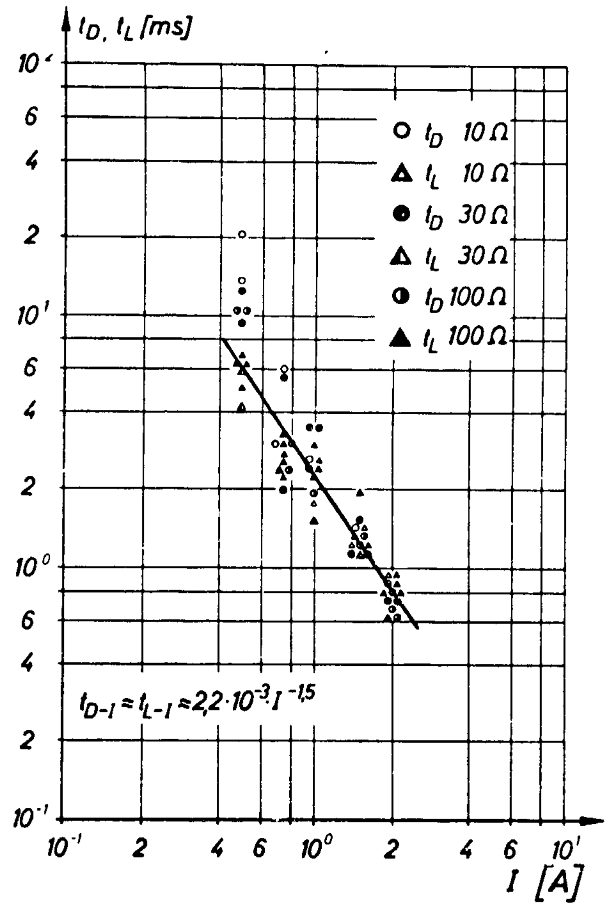

Figure 19. Time difference t between ignition pulse and breakage of the bridge wire or light emission as a function of the impressed current I for the P 65 igniter, with the series resistance as parameter.

Therefore, the current flowing now is

$$I = \frac{102\ [V]}{100 + 100\ [\Omega]} = 0{,}51\ [A] \tag{19}$$

With the momentary resistance of 100 ohms, the voltage drop across the igniter is now

$$U = 0{,}51\ [A] \cdot 100\ [\Omega] = 51\ [V] \tag{20}$$

so that a power of

$$N = U \cdot I = 51\ [V] \cdot 0{,}51\ [A] = 26{,}01\ [W] \tag{21}$$

is now converted at the igniter, and rapidly produces a reaction in the ignition mixture. As can be seen from the oscillogram (example in Figure 17), this resistance range is even passed through several times because of the flutter phenomenon.

For comparison, let us discuss the conditions at "constant" voltage.

A constant voltage of 2 V is applied to the igniter, with 2 ohms, so that the current flowing is

$$I = \frac{U}{R} = \frac{2\ [V]}{2\ [\Omega]} = 1\ [A] \tag{22}$$

Then the power applied to the igniter, N, is likewise

$$N = U \cdot I = 2\ [V] \cdot 1\ [A] = 2\ [W] \tag{23}$$

So far the conditions at constant voltage are still entirely identical with these at constant current. But if we assume that on breakage of the bridge wire, it passes through a resistance of 100 ohms, then there flows only a current I of

$$I = \frac{2\ [V]}{100\ [\Omega]} = 0{,}02\ [A] \tag{24}$$

Now only a power, N, of

$$N = U \cdot I = 2\ [V] \cdot 0{,}02\ [A] = 0{,}04\ [W] \tag{25}$$

is converted. This is only 1/650 of the power with constant current, although the initial conditions were selected for a constant, identical 2 watt power conversion at the igniter.

From this simple calculation it becomes apparent why the time delays for wire breakage and light emission are very close together for constant current, in contrast to constant voltage.

3.5 Application of a Current Pulse

As the time difference between the ignition pulse and breakage of the igniter wire or light emission is not representative of the time t in the energy formula (1) either for low voltages at the igniter or for the constant voltage method, or even for the constant current method, a pulse circuit was built with an adjustable time for constant current. Here a constant current can be applied to the igniter for an adjustable time duration. The voltage drop at the igniter is again measured with the oscilloscope. The energy requirement is determined from the previously given product U · I · t. With a selected constant current, the pulse time t was increased by steps for each igniter until the igniter responded. /35

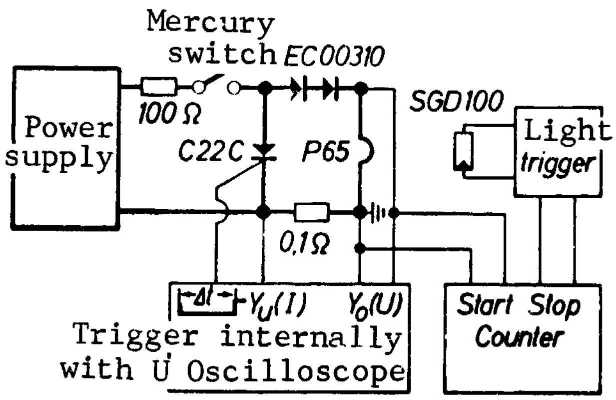

Figure 20. Simple circuit for application of constant current pulses of adjustable length to low-resistance igniters or electrical detonators.

Figure 20 shows the circuit design. By using series resistances of 10, 30, or 100 ohms, in comparison to the igniter resistance of 2 ohms, one obtains a current generator with almost constant current. The current was switched to the igniter by means of a mercury switch. A Tektronix Type 556 oscilloscope was triggered with the ignition pulse. The trigger pulse started both the first sweep generator for the oscillographic recording and a second sweep generator in the device. The second sweep generator produces an output pulse after a time which is adjustable with a Helipot. This controlled a controllable four-layer diode, Type C22C in parallel with the P 65 igniter, which short-circuited the ignition circuit. To keep the residual voltage drop of the four-layer diode from still being applied to the igniter, two silicon diodes were connected in series, in the direction of transmission, ahead of the P 65 igniter in the ignition circuit, so that procatically no residual voltage was applied to the P 65 igniter after the four-layer diode was switched on. In contrast to the previous experiments, the current curve in the ignition circuit was measured with a low resistance of 0.1 ohm. The voltage drop across this shunt was likewise recorded with the oscilloscope. This now included also the DC portion. Figure 21 shows a typical oscillogram.

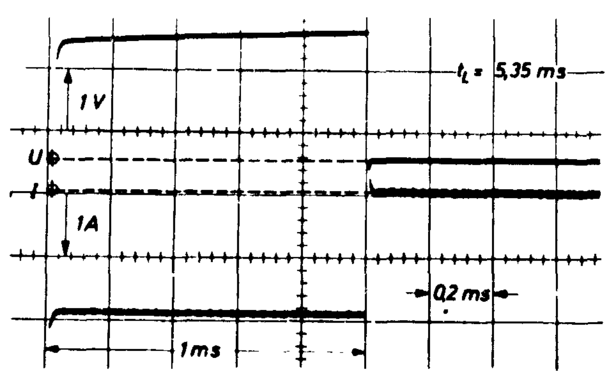

Figure 21. Example of the current and voltage curves for two P 65 igniters connected in parallel with a current pulse of 2 A and a duration of 1 ms, according to the circuit of Figure 20.

The voltage deflection is upward, while the positive current deflection is downward. With this measuring system the time to wire breakage cannot be measured, and the cost of the circuit which would be needed was not considered necessary. As in the previous experiments, the time difference between the ignition pulse and light emission was measured with a counter.

All the measurements of the time difference t between the ignition pulse and light emission for the P 65 ignitor for application of current pulses with the limiting energy are plotted as a function of the current, I, in the log-log diagram of Figure 22, with the series resistance as the parameter. As can be seen, the separate measurements scatter relatively severely, showing no significance for the differing series resistances of 10, 30, and 100 ohms. As the range from 0.5 to 2 A of current was very small, an average line can only be plotted poorly for the very scattered measurements. The measurements would justify lines according to the equation

$$t_{L-Imp} = 3{,}5 \cdot 10^{-3} I^{-1} \tag{26}$$

or

$$t_{L-Imp} = 2{,}8 \cdot 10^{-3} I^{-1/1{,}33} \tag{27}$$

or

$$t_{L-Imp} = 2{,}5 \cdot 10^{-3} I^{-1/1{,}5} \tag{28}$$

By substituting U for I, we obtain the following equations: /36

$$t_{L-Imp} = 7 \cdot 10^{[illegible]} \cdot U^{[illegible]} \tag{29}$$

$$t_{L-Imp} = 7 \cdot 10^{[illegible]} U^{[illegible]} \tag{30}$$

$$t_{L-Imp} = 7 \cdot 10^{[illegible]} U^{[illegible]} \tag{31}$$

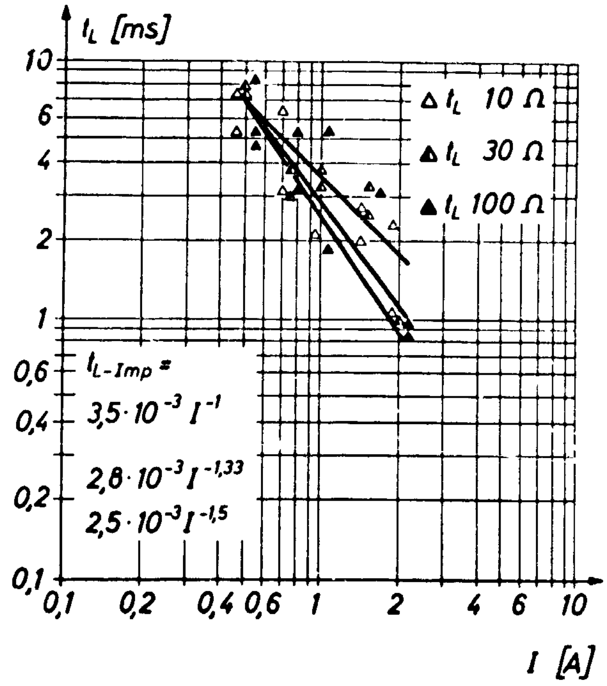

Figure 22. Time difference t between ignition pulse and light emission for the P 65 igniter for application of current pulses at the limiting energy, as a function of the constant current I, with the series resistance as parameter, on log-log scale.

Except for a minor variation in constants, which is within the accuracy of the measurement, Equations (26) and (20) correspond to Equation (11) for the time difference between the ignition pulse and light emission on application of constant voltage. Equations (28) and (31) correspond broadly to the equation with application of constant current, (14) or (15).

As has already been mentioned, however, the range of measurements studied is very small, so that the reliability of the equations is slight. It is worth noting, however, that one obtains the same time differences between the ignition pulse and light emission in spite of quite different ways of applying the stress, such as application of constant voltage, constant

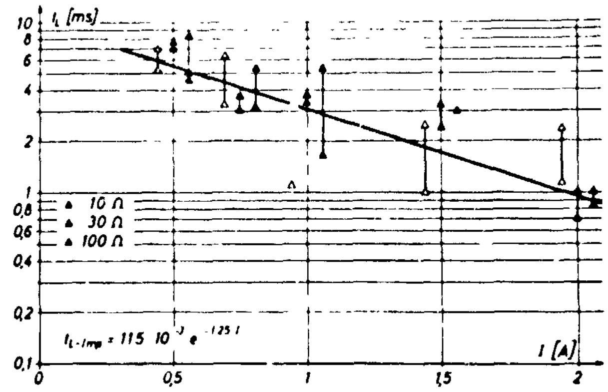

Figure 23. Time difference t between ignition pulse and light emission for the P 65 igniter on application of current pulses with the limiting energy, as a function of the current, I, in a semi-logarithmic plot with the series resistance as parameter.

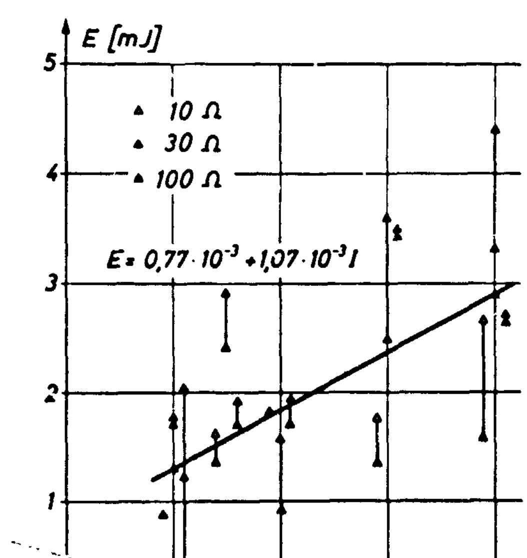

Figure 24. Limiting energy, E_{Imp} of the P 65 igniter from application of current pulses, as a function of the current, with the series resistance as parameter.

current, or current pulses, in the current range from 0.5 to 2 A. That is, the time here is determined primarily by the reaction time of the ignition mixture.

If we plot the time differences, t_{L-Imp}, versus the current in a semi-logarithmic plot, then the individual measurements can be fit somewhat better by a line like that shown in Figure 23.

In this plot, the line corresponds to an exponential function with the following equation:

$$t_{L-Imp} = 11{,}5 \cdot 10^{[illegible]} \cdot C^{[illegible]} \quad (32)$$

But it must still be emphasized that this equation only reproduces relatively well the measurements in the range from 0.5 - 2 A, and it cannot be extrapolated either to smaller or to larger currents.

As was mentioned, the pulse duration, t_{Imp}, at a prescribed current was extended until the igniter responded. From the time duration t_{Imp} obtained in this way, it is possible to calculate the energy by the formula (1):

$$E_{Imp} = U \cdot I \cdot t_{Imp}$$

where t_{Imp} is the shortest pulse duration at which the igniter responds, I the preset current, and U the voltage drop measured from the oscillogram.

In Figure 24, the limiting energy E_{Imp} for the P 65 igniter, calculated in this way, is plotted as a function of the current with the series resistance as parameter. Here, too, the measurements of the limiting energy scatter very severely. They rise surprisingly with increasing current in the region studied. This is surprising because a lower energy requirement had been expected for application of higher current. As already mentioned, the loss through conduction of heat would be more important at lower power input.

For simplicity, the very scattered values in the narrow measurement range were represented by a straight line with the following equation:

$$E_{Imp} = 0{,}77 \cdot 10^{-3} + 1{,}07 \cdot 10^{-3} I \qquad (33)$$

It must particularly be emphasized that this equation applies only in the small range from 0.5 to 2.0 Amperes. This range is near the limiting current of 0.35 Amperes.

Unfortunately, no measurements were made at considerably higher currents up to 50 Amperes, for example. They might have led to a more reliable statement about the behavior of P 65 igniters on application of constant current; but, as explained initially, the problem posed was to determine the energy requirement of the igniter at low voltage or current levels.

4. ENERGY COMPARISON

It is interesting to compare the energy values obtained from the measurements by the various testing methods if the time differences between the ignition pulse and the result, light emission or wire breakage, are inserted uncritically into the formula /37

$$E = U \cdot I \cdot t \qquad (1)$$

or

$$E = \int_{0}^{t\ \mathrm{result}} U(t) \cdot I(t) \cdot dt \qquad (1a)$$

Figure 4 shows the time difference between the ignition pulse and light emission as a function of the current, from the Gevelot company data [1] and the energy requirement calculated from it.

The numerical values are listed again in the Table (Figure 25) for 0.5, 1 and 2 A.

For capacitor discharge, the energy requirement for these igniters remains constant at about 3 mJ (see Figure 8) — even for a capacitance range from 0.1 - 1,000 μF. Here, the energy requirement is calculated by the equation

$$E_C = 1/2 \cdot C \cdot U^2 \qquad (2a)$$

If we insert into the energy formula (1) the time difference between the ignition pulse and light emission at constant voltage, the formula would give the energy requirement at

$$E_{L-U} = U \cdot I \cdot t_{L-U} = 3{,}25 \cdot 10^{-3} \cdot U = 6{,}5 \cdot 10^{-3} \cdot I, \qquad (34)$$

because, according to Equation (11),

$$t_{L-U} = 6{,}5 \cdot 10^{-3} \cdot U^{-1} \qquad (11)$$

As Figure 16 shows, there is a break in the time difference t_{D-U} between the ignition pulse and the wire breakage when constant voltage is applied, so that the voltage range between 0.75 and 4 V is most practically represented by the equation

$$t_{D-U,1} = 32 \cdot 10^{-3} \cdot U^{-2{,}5} \qquad (12)$$

from which we can calculate the energy requirement

$$E_{D-U,1} = U \cdot I \cdot t_{D-U,1} = 16 \cdot 10^{-3} \cdot U^{-0{,}5} = 11{,}3 \cdot 10^{-3} I^{-0{,}5} \qquad (35)$$

This equation would state that the energy requirement becomes smaller with increasing voltage or current.

But if we proceed to higher voltages than 4 V, then the times to wire breakage as a function of the voltage are represented by the equation

$$t_{D-U,2} = 7 \cdot 10^{-3} \cdot U^{-1,5} \tag{13}$$

from which we would obtain this equation for the energy requirement:

$$E_{D-U,2} = U \cdot I \cdot t_{D-U,2} = 3,5 \cdot 10^{-3} U^{0,5} = 5 \cdot 10^{-3} I^{0,5} \tag{36}$$

According to this, the energy requirement would increase with the square root of the voltage or of the current.

Current A	Voltage drop V	$E_{Gevelot}$ $10^{-3}J$	E_C $10^{-3}J$	E_{L-U} $10^{-3}J$	E_{D-U1} $10^{-3}J$	E_{D-U2} $10^{-3}J$	$E_{L,D-I}$ $10^{-3}J$	E_{Imp} $10^{-3}J$
According to equation		34	2a	11	12	13	14	3.
0,5	1	3,5	3	3,25	16	3,5	3,1	1,3
1	2	5,4	3	6,5	11,3	5,0	4,4	1,8
2	4	13,4	3	13,0	3,0	7,0	6,2	2,9

$E_{Gevelot} = 3 \cdot 10^{-3} U = 6 \cdot 10^{-3} I$

$E_C = 1/2\, CU^2 = 3\ mJ$

$E_{L-U} = U \cdot I\, t_{L-U} = 3,25 \cdot 10^{-3} U = 6,5\ 10^{-3} I$ (34), da $t_{L-U} = 6,5 \cdot 10^{-3} U^{-1}$ (11)

$E_{D-U,1} = U \cdot I\, t_{D-U,1} = 16\ 10^{-3} U^{-0,5} = 11,3 \cdot 10^{-3} I^{-0,5}$ (35), da $t_{D-U,1} = 32\ 10^{-3} U^{-2,5}$ (12)

$E_{D-U,2} = U I \cdot t_{D-U,2} = 3,5 \cdot 10^{-3} U^{0,5} = 5 \cdot 10^{-3} I^{0,5}$ (36), da $t_{D-U,2} = 7 \cdot 10^{-3} U^{-1,5}$ (13)

$E_{L,D-I} = U \cdot I \cdot t_{L,D-I} = 3,1 \cdot 10^{-3} U^{0,5} = 4,4 \cdot 10^{-3} I^{0,5}$ (37), da $t_{L,D-I} = 6,2 \cdot 10^{-3} U^{-1,5}$ (14)

$E_{Imp} = U \cdot I \cdot t_{Imp} = 0,77 \cdot 10^{-3} + 0,535 \cdot 10^{-3} U = 0,77 \cdot 10^{-3} + 1,07 \cdot 10^{-3} I$ (33)

Figure 25. Comparison of the limiting energy values for response of P 65 igniters at 0.5, 1 and 2 A, and 1, 2, and 4 V, obtained from the various measuring procedures if the values were accepted uncritically. However, only the values of E_c and E_{Imp} can be considered correct.

We also obtain this formula if we apply constant current to to the igniters instead of constant voltage. From the measurements, which were, to be sure, obtained only in a small current range, from 0.5 to 2 A, the formula for the time delay between the ignition pulse and light emission or wire breakage can be reproduced by the equation

$$t_{L,D-I} = 6{,}2 \cdot 10^{-3} \cdot U^{1{,}5} \tag{15}$$

This would yield the energy equation

$$E_{L,D-I} = U \cdot I \cdot t_{L,D-I} = 3{,}1 \cdot 10^{-3} U^{0{,}5} = 4{,}4 \cdot 10^{-3} I^{0{,}5} \tag{37}$$

This equation, (37), corresponds broadly with Equation (36). The slight variation in the constants is within the accuracy of the measurements.

As has already been mentioned several times, however, the time difference between the ignition pulse and light emission, as well as that for bridge wire breakage, is not representative of the time requirement needed to calculate the energy requirement for the bridge igniter according to Equation (1). For this reason, we did experiments with a pulse method so as to measure the minimum energy requirement for the P 65 igniters at constant current. Unfortunately, the limiting energy values vary quite severely in the current range of 0.5 to 2 A (which is the only range of interest for the author). Thus, the linear dependence we have established between the energy requirement and the ignition pulse, according to Equation

$$E_{Imp} = 0{,}77 \cdot 10^{-3} + 1{,}07 \cdot 10^{-3} \cdot I = 0{,}77 \cdot 10^{-3} + 0{,}535 \cdot 10^{-3} U \tag{33}$$

can be considered only as a first rough approximation. Nevertheless, particularly at 0.5 and 1 A, this formula yields the minimum energy values necessary to fire the bridge igniters, while at 2 A the energy requirement is about that for capacitor discharge (Figure 25, p 48).

All the energy values calculated from the formulas are collected in the Table (Figure 25). Here it must again be emphasized that only the energy data for capacitor discharge, E_C, /38 or the energy requirement determined with the pulse method, E_{Imp}, can be regarded as correct.

5. CONCLUSION

The author has assembled the various methods by which the energy and power requirements of "electro-explosive elements" can be studied, using the P 65 igniter as an example, so as to give the interested reader a comparison with his own measuring methods and results.

Unfortunately, there are in the literature only very few works on the behavior of electrical igniters and electrical detonators, and these have studied only a very narrowly limited range of voltage and current. The author considers that it would be desirable, in order to be able to make a fundamental scientific evaluation of these elements, for the various institutions concerned with electro-explosive elements to publish their results, even if they are only partial. Everyone interested could learn from the increased exchange of experience, and we could build even more dependable devices with electro-explosive elements.

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